Excitonic Superfluid and Supersolid Phases of Electron-Hole Bilayers

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ABSTRACT:

Electron-hole bilayers, in which the distance between the layers is comparable to the typical distance between carriers within a single layer, support a rich variety of ground states including the excitonic dipolar superfluid and Wigner crystal of phase-coherent excitons. We present theoretical predictions and recent experimental results on electron-hole bilayer systems.

Motivation

Bilayer quantum wells in semiconductor heterojunctions, where carriers in one layer are electrons and carriers in the other layer are holes, are one of the promising candidates for a Bose-Einstein condensate (BEC) of excitons. When the distance *d* between layers is small compared to the typical distance between carriers within each layer, excitons (bound states of electron-hole pairs) resulting from the attractive Coulomb interaction between electrons and holes, form a dilute Bose gas and undergo condensation.
The exciton BEC in semiconductors was first predicted by Keldysh in 1965, but its experimental realizations has been elusive.

The formation and properties of excitonic condensates in *double quantum wells* is a subject of ongoing debate. Although these systems are not truly superfluid - the *U(1)* symmetry associated with the phase of the exciton order parameter is not an exact symmetry - various signatures of excitonic condensation can be probed provided that the excitons are long lived. At present, there are three main candidates for realization of excitonic condensate in double quantum wells: bilayers in which electron-hole plasma is created by optical pumping and then spatially separated by electric field to create indirect excitons, bilayer electron-electron quantum Hall systems near filling factor one, and undoped bilayers in which carrier density in each layer can be independently controlled by an external gate associated with that layer. In the first system, the condensation is detected *a posteriori* by photoluminescence measurements of electron-hole recombination and the electromagnetic response of excitons is not yet accessible. Bilayer quantum Hall systems show promising signatures of excitonic condensation, albeit over the vacuum of a fully filled Landau level. Because of the non-trivial electromagnetic response of this "vacuum", the transport properties of this system are different from those of a true excitonic condensate.

Therefore, we focus on the third candidate, independently contacted electron-hole bilayers. We discuss the phase diagram of this system, and predictions that follow from a hydrodynamic model. Then we discuss recent experimental progress and results towards realization of electron-hole bilayers devices. Including transport and Coulomb drag measurements.

Theory: Phase Diagram of Bilayer System

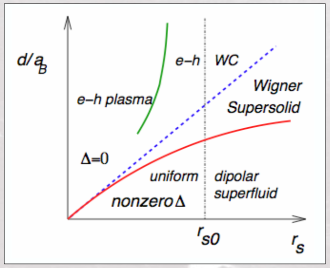


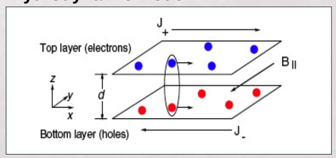
Figure 1: Schematic phase diagram of bilayer electron-hole system. The phases below the dia

We consider a bilayer system with electrons in the bottom layer and holes in the top layer (Fig. 2). This system is characterized by two constants. The first (d/a_B) is distance between layers measured in units of Bohr radius of carriers. The second (r_s) is the ratio of potential and kinetic energy of carriers within a single layer. When $d/a_B > r_s$, interlayer potential energy is greater is that the intralayer potential energy, and the two layers are decoupled (region above the dotted blue diagonal in Fig. 1). In this regime, the system goes from a uniform electron hole plasma to a state with uncorrelated electron and hole Wigner crystals when $r_s > r_{s0} \sim 37$.

When $d/a_B < 1$, the two layers are coupled or phase coherent (region below the dotted blue diagonal in Fig. 1). In this regime, the system can be modeled as a system of excitons with repulsive dipolar interaction. **In the dilute limit, as expected, the excitons condense into a uniform dipolar superfluid.** When the density of excitons or, equivalently, the dipolar repulsion is increased, the system undergoes crystallization to minimize the potential energy. A qualitative analysis shows that this occurs In the region $r_s^{1/2} << d/a_B < r_s$ (region between the diagonal and the red line). **This ground state has a spontaneously broken translational symmetry as well as phase-coherence among all excitons; it is a supersolid.**

Next, we discuss briefly the properties of excitonic state using a hydrodynamic model.

Hydrodynamic Model



We use coordinate system in which the hole (electron) coordinates are given by $\mathbf{r}_h = \mathbf{r} + \mathbf{d}/2$ ($\mathbf{r}_e = \mathbf{r} - \mathbf{d}/2$) where $\mathbf{r}$ is a two dimensional position vector and $\mathbf{d}$ is a vector normal to the layers. An excitons in this system has a nonzero dipole moment given by $\mathbf{p} = 2e\mathbf{d}$. At low energies, the phase of excitons or the dipolar phase is the only relevant degree freedom. The coupling of the dipolar phase with external gauge potentials is obtained by minimally coupling the constituents of the exciton (the electron and the hole) with gauge potential:

$$\nabla\Phi_d \rightarrow \nabla\Phi_d - e\mathbf{A}_e + e\mathbf{A}_h$$

Since the dipolar phase couples to the antisymmetric gauge potential $\mathbf{a} = (\mathbf{A}_e - \mathbf{A}_h)$, it follows that changing the antisymmetric gauge potential $\mathbf{a}$ will induce dipolar supercurrent in the condensate. For example, consider a uniform magnetic field $\mathbf{B}_y = -B_{||}$ generated by a gauge potential $\mathbf{A}_x = -B_{||}z$ (Fig. 2). It then follows, from analogy with a superconductor, that the dipolar supercurrent $\mathbf{J}_d$ will be given by

$$\mathbf{J}_d = 2e^2\rho_d\mathbf{B}_{||} \times \mathbf{d}$$

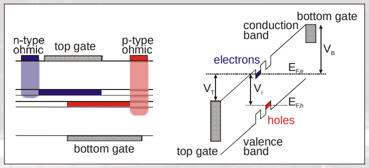
Thus, we predict that a uniform in-plane magnetic field will produce persistent and opposite currents in the two layers in a direction perpendicular to the magnetic field. This result is a direct consequence of the non compensation of gauge potentials acting on the electron and the hole, which are necessarily separated by distance *d*. We can understand the persistent dipolar current as arising from the "perfect diamagnetism" of electrons and holes, in conjunction with the paucity of low-energy excitations in a superfluid.

Implementation of Electron-Hole Bilayers in GaAs/AlGaAs

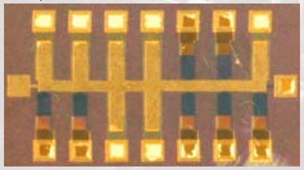
The experimental implementation of electron-hole bilayers for transport experiments requires:

- Closely spaced layers (10 - 30 nm barriers)
- Low density
- Low carrier temperatures ~ 1K
- High mobility ~ 10^5 Vs/cm^2

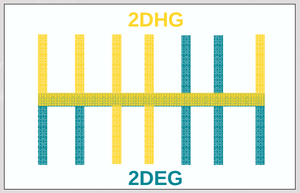
A schematic view of the independent contact scheme and corresponding band structure is shown below.



A photograph of a fully processed undoped electron hole bilayer device with a mesa width of 100 μm. This structure can be used to measure longitudinal and Hall resistance in addition to Coulomb drag and other transport effects

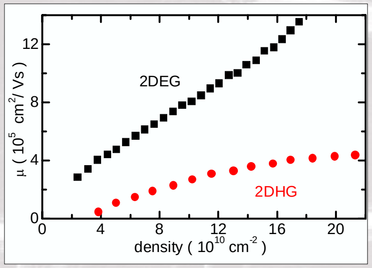


The two-dimensional electron gas (2DEG) is beneath the area gated from the top shown in blue. The two-dimensional hole gas (2DHG) is beneath the bottom gate seen in gold.

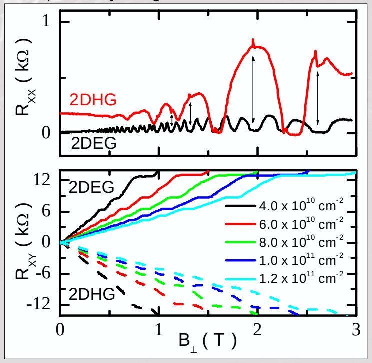


Independently Contacted Transport Experiments

Three voltages (V_T, V_I, & V_B) are used to determine the densities of the 2DEG and 2DHG. The mobility versus density for the 2DEG and 2DHG is shown below for various values of V_T, V_I, & V_B.



Below are magnetoresistance traces for the 2DEG and 2DHG at unmatched densities. Notice that as the 2DEG goes into a quantum hall state, the resistance of the 2DHG changes. This is an affects of incompressibility being seen in the SdH oscillations.



Above the Hall resistance is plotted at balanced n and p from 1.2 x 10^{11} cm^{-2} down to 4.0 x 10^{10} cm^{-2}. The opposing Hall slopes verify the charge of the carriers.

Coulomb drag and in-plane field measurements are in progress.

Collaborators: Peter B. Littlewood, Sankar Das Sarma, John A. Seamons

For further details, see Phys. Rev. Lett. **93**, 266801 (2004), Phys. Rev. B **72**, 205313 (2005), Phys Rev. B **74**, 233302 (2006), and cond-mat/0611220